THE QUEST FOR GRAVITY WAVE B-MODES

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One of the most exciting quests in all of contemporary science is to find hints that in the first tiny fraction of a second after the Big-Bang the Universe hyper-inflated by a factor of $\sim 10^{60}$. Such inflation will have injected gravity waves into the fabric of spacetime which will in turn have left a faint imprint in the polarization pattern of the Cosmic Microwave Background. This paper describes the history of polarization measurement, the experimental optimization of this latest search for the gravity wave imprint, and the current round of experiments and their various approaches to the challenge.

1 Introduction

The study of the anisotropy of the Cosmic Microwave Background (CMB) has taught us much about the origin, content and fate of the Universe in which we find ourselves, and is one of the cornerstones of what has come to be called the standard cosmological model (LCDM). In this model the Universe began in a hot "Big-Bang" approximately 14 billion years ago and has been expanding and cooling ever since — around 400,000 years after the beginning it made the transition from plasma (opaque) to neutral gas (transparent) and the CMB is the highly re-shifted hot-object (black-body) light which has been freely streaming through the Universe ever since. It therefore offers us a snapshot of the density pattern at this time of "last scattering" on a spherical shell around the location where our galaxy would later form. Measurements of the total intensity (T) pattern by ground-based and balloon-borne instruments had by 2003 resulted in stringent cosmological constraints [1], which were confirmed by the WMAP spacecraft, and will shortly be further improved upon by the Planck space mission.

Meanwhile efforts to observe the predicted polarization of the CMB intensified and in 2002 the DASI experiment announced the first detection [2]. The "headless vector" polarization pattern on the sphere can be broken down into two scalar quantities dubbed E-modes and B-modes [3]. If the electrons at last scattering are exposed to radiation fields which have a quadrupolar

component then Thompson scattering results in a net polarization. Flows of material generate such quadrupoles via Doppler shifts along the direction of flow resulting in a "pure gradient" or E-mode pattern. Since those flows are sourced by the density perturbations, correlations between the T and E patterns also naturally result. After last scattering the purity of the initial E-mode pattern is slightly disrupted by small gravitational deflections of the CMB photons as they travel to us through the forming large scale structure. This leads to a B-mode within the base model which is referred to as the "lensing B-mode".

While the basic LCDM model is enormously successful it leaves several fundamental questions unanswered. From the earliest calculations it was conventional to assume a flat power law initial perturbation spectrum coming out of the Big-Bang [4]. There was no real reason to do so other than simplicity, but, quite remarkably, recent CMB observations have proven it to be very close to the truth! Later the cosmo-genic theory known as Inflation was invented [5] which naturally predicts such an initial perturbation spectrum and also makes several other predictions which have subsequently proven to be true, such as the global flatness of space ($\Omega_{tot} = 1$) and the small degree of large scale anisotropy.

However Inflation is a radical theory positing expansion of space by a vast factor ($\sim 10^{60}$) occurring at an incredibly early time ($\sim 10^{-35}$ s), and hence at energies ($\sim 10^{16}$ GeV) far, far above anything probed by terrestrial experiment. Such radical ideas must be tested in all possible ways. Fortunately inflation makes an additional prediction — it injects a background of gravitational waves (aka tensor perturbations) into the Universe which have been propagating through it ever since. These distortions of the fabric of spacetime will induce additional quadrupolar moments in the radiation field incident on the electrons at last scattering which will in turn result in both E-mode and B-mode polarization — see figure 1. The magnitude of the gravity wave component is conventionally described by the tensor to scalar ratio denoted by r.

The motivations for making measurements of CMB polarization can be summarized as follows:

- Measuring the E and TE spectra tests the basic LCDM paradigm. At larger angular scales there is additional information to be had regarding the process of reionization [6].
- Measuring lensing B-modes at smaller angular scales can provide information about structure formation, and in particular neutrino mass.
- Measuring B-modes at intermediate and large angular scales holds out the tantalizing possibility of detecting Inflationary gravity waves — this has been referred to as the "smoking gun of inflation".
- The TB and EB spectra are identically zero in the standard paradigm. However alternate Lorentz violating models might produce a signal here [7].

2 Review of CMB Polarization Measurements to Date

The first detection of CMB polarization was reported by the DASI experiment in 2002 [2]. Measuring over a broad range of angular scales around $\ell \sim 200$ the E-mode was found to be consistent with the LCDM expectation and inconsistent with zero at around the $\sim 5\sigma$ level, whereas the B-mode was consistent with zero as expected.

In 2003 WMAP reported high significance detections of TE correlation and the somewhat surprising result of a strong reionization contribution at large angular scales [6], although this result was later partially retracted.

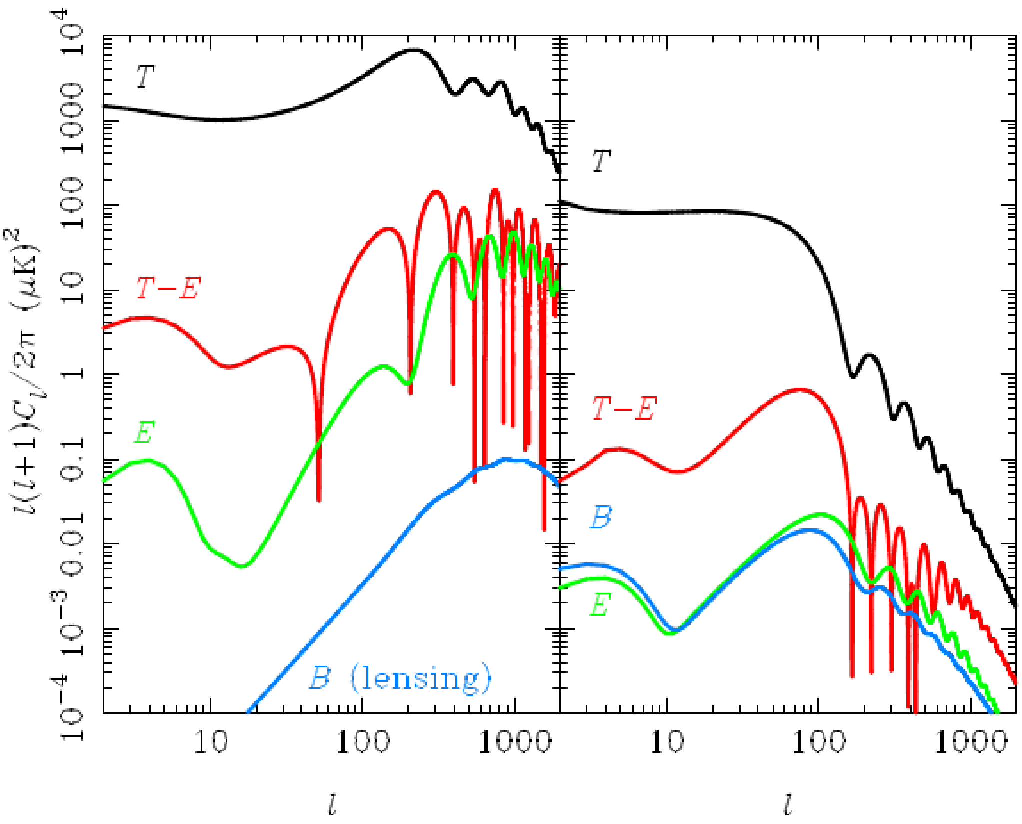

Figure 1: Theoretical CMB power spectra showing the basic T, E and TE contributions from density perturbations at left, along with the B-mode resulting from lensing of that initial E-mode. The tensor contribution from inflationary gravity waves to each spectrum is shown at right for $r = 0.2$. We see that the inflationary B-mode at $\ell \lesssim 100$ is potentially detectable. (Figure courtesy of A. Challinor)

To date $\sim$ 10 experiments have reported detections of E and TE with only upper limits on B-modes to date — Figure 2 shows the current situation. At the moment the QUAD [8] and BICEP1 [9] experiments lead the field at smaller and intermediate angular scales respectively, with WMAP providing the only available information at the largest scales.

3 Optimizing the Quest for Gravity Wave B-modes

The current best limit is $r < 0.17$ [10] from WMAP7+SPT temperature data [a]. However such T based limits are now cosmic variance limited and to go further we must search for B-modes. As we see in figure 1 there are two regions where the detectability is maximized: the "recombination bump" around $\ell \sim 80$ and the "reionization bump" at $\ell < 10$. Clearly the recombination bump is potentially lost in the rapidly rising lensing induced B-mode. However to measure low multipoles one must use a large fraction of the celestial sphere — and much of it is obscured by foreground emission from our own galaxy. There is hence a complex trade-off between sky area and observing frequencies when deciding how best to target this experimental goal.

3.1 Galactic foregrounds and optimum observing frequency

At low (< 30 GHz) frequencies the sky brightness is dominated by synchrotron radiation from relativistic electrons spiraling in the magnetic fields of the galactic ISM (inter stellar medium).

[a] As we see in Figure 1 gravity waves will add power to all spectra including T.

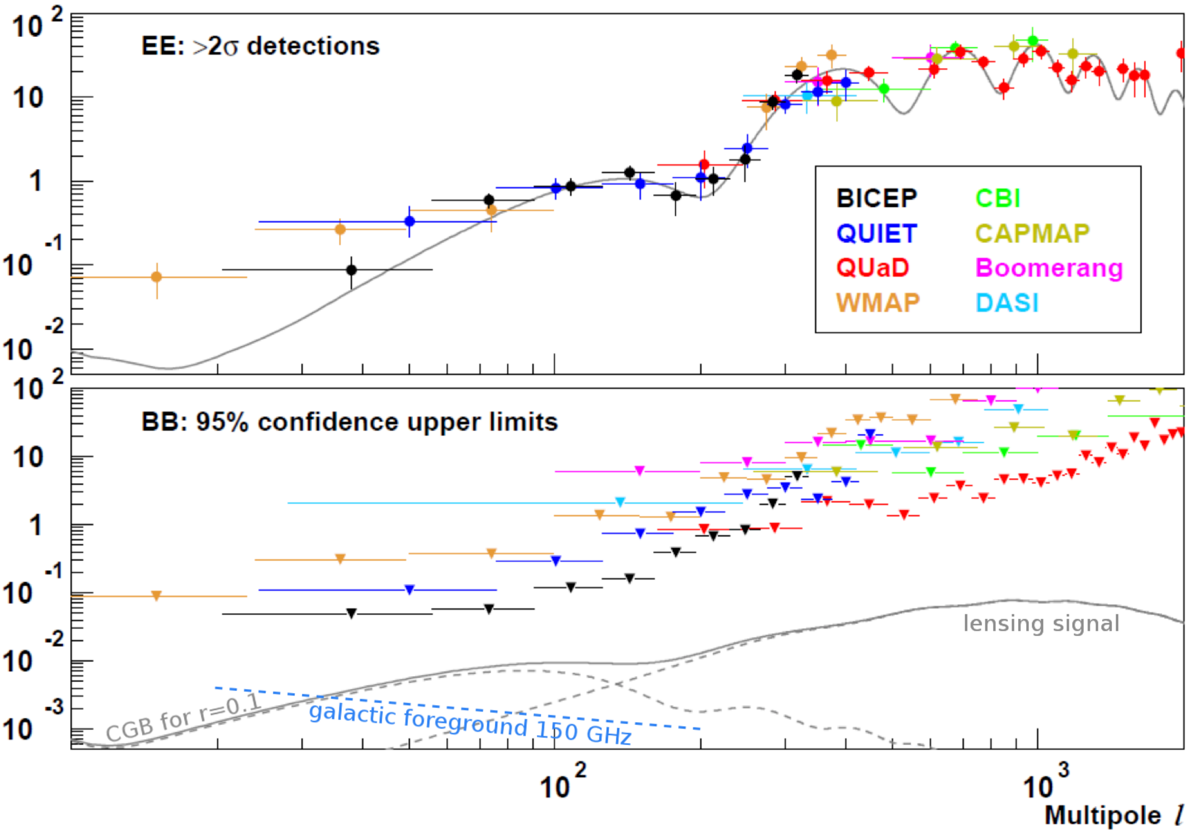

Figure 2: Current results on CMB polarization. The upper panel shows E-mode results compared to the standard LCDM expectation. The lower panel shows 95% upper limits on B-modes, with the dashed gray lines indicating B-mode signals from lensing and a possible gravity wave signal with $r = 0.1$; the solid gray line is the sum of these two signals. The dashed blue line indicates an estimate of the B-mode signal from Galactic foregrounds (both synchrotron and dust) at 150 GHz in a small, clean patch of sky. (Adapted from Chiang et al. (2009) with the addition of more recent points from the QUIET experiment and the foreground projections.)

At higher ($>$ 300 GHz) frequencies emission from galactic dust is dominant. Since the dust is cold it is confined to a thin disk, whereas the high energy electrons have a much larger scale height and fill the galactic halo. It is a fortunate accident that the peak brightness of the 2.7 K CMB black body radiation at $\sim$ 150 GHz is close to the minimum of the total galactic emission.

It is very important to note that the maximum of the ratio of CMB brightness to sync+dust is a function of galactic latitude — close to the disk one wants to go to lower frequencies to get away from dust, whereas at high latitude the optimum frequency shifts up as we see in Figure 3. One must therefore be very careful of statements implying there is a single best observing frequency — such statements always carry an implicit assumption as to the required sky area.

Moving from total intensity to polarization leads to additional complications since the polarization fraction differs between synchrotron and dust, and with position on the sky. To connect the two requires (highly uncertain) modeling of the galactic magnetic field — see for example [12]. The best current information comes from WMAP at low frequencies and from extrapolations from IRAS at high frequencies. Figure 3 shows a projection — information from Planck will shortly massively increase our knowledge of polarized foregrounds.

3.2 Small patch or big patch?

If one decides to target the reionization bump there is no choice as to sky coverage — to resolve modes at $\ell < 10$ one needs as large a fraction of the sky as possible. Since we already know

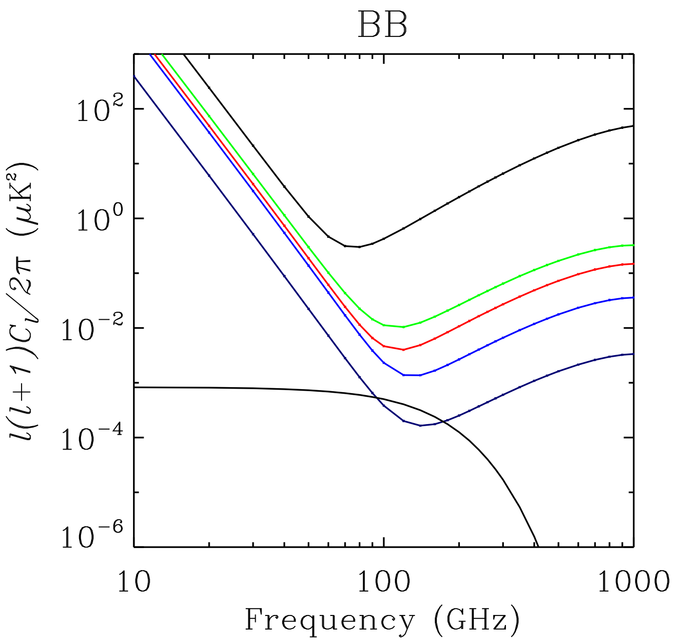

Figure 3: The colored lines show the total projected polarized galactic emission at angular scales of $80 < \ell < 120$ as a function of frequency for sky coverage: from top to bottom, full, galactic latitude greater than 10, 30, and 50 degrees, and for a clean patch with radius of 10 degrees. The lower black line shows the inflationary B-mode for $r = 0.01$. We see the asymmetry between dust and synchrotron foregrounds — (high frequency) dust emission falls much more rapidly with increasing galactic latitude causing the optimum frequency of observation to shift up from < 100 GHz towards 150 GHz. (Reproduced from Dunkley et al. (2008).)

$r \lesssim 0.2$ this means that heavy foreground "cleaning" will be required to reach the cosmological signal. This dictates making measurements at several frequencies and decomposing them as sums of multiple components — a well established technique in WMAP (and now Planck) analysis. The ultimate limitations of cleaning are hard to predict but the prospect of pulling out "ghost-like" $\ell < 10$ cosmological B-modes which are submerged by many orders of magnitude beneath galactic foreground is daunting to say the least. Nevertheless the projected ability to set limits of $r \lesssim 0.03$ with Planck has been claimed [13]. Measuring close to the whole sky at many frequencies is something that many would claim is only possible in space [b].

If one instead chooses to target the recombination bump there is a huge benefit — we can focus on small patches of sky at high galactic latitude which have foreground contamination at least an order of magnitude lower. From a simplistic signal-to-noise point of view when aiming for an initial detection one wants to concentrate the available sensitivity onto as small a patch of sky as possible. The lower limit is then set by the need for the patch to be at least as big as the largest angular scale of interest. Since the E and B mode patterns are non-local in practice one needs a patch several times larger than this to maintain separability [14]. In practice when targeting the $\ell \sim 80$ recombination bump a patch of area ~ 500 square degrees is appropriate.

3.3 Angular resolution

Once one has decided the observing frequency, and patch of sky to be observed, the remaining variable is the size of the telescope aperture — the angular resolution. In principle the requirement is modest — the angular scale corresponding to $\ell \sim 80$ is adequately resolved by a 25 cm aperture at 150 GHz.

However if higher angular resolution and sufficient sensitivity are available then the lensing

[b] But see the PIPER and CLASS experiments in Section 4.

contribution at larger angular scales can be computed and subtracted in a map sense — the lensing component can be cleaned out. From Figure 2 we see that this becomes necessary around $r \sim 0.01$. In addition, of course, measuring the lensing B-modes is an important goal in of itself allowing several scientific results including constraints on the neutrino mass.

3.4 Detector Technologies

The two main detector technologies used for CMB detection are bolometers (photons go to heat) and coherent amplifiers (photons go to voltage on a wire). Either of these can be used in direct imaging (telescope beam scans around on the sky) or interferometric systems (multiple telescopes "stare" at the sky and outputs are cross correlated). The DASI and CBI experiments were 30 GHz interferometers based on (coherent) HEMT amplifiers. The WMAP, CAPMAP and QUIET experiments were direct imaging HEMT based systems. The other experiments shown in Figure 2 (Boomerang, QUaD and BICEP) were direct imaging bolometer systems. To date bolometer experiments have held the edge in terms of per detector sensitivity.

3.5 Polarization Modulation and Beam Systematics

To measure linear polarization anisotropy in a direct imaging experiment one needs to measure brightness differences scanning across the sky with detectors sensitive to different polarization directions. Even from the best sites on the ground one is looking at the CMB through a "glowing screen" whose brightness variations are many times the size of the CMB anisotropies (think clouds). This problem is mostly alleviated on balloons or in space, but all detectors are subject to intrinsic fluctuations ($1/f$ noise) at low frequencies which have a similar practical effect. However the atmospheric emission is largely unpolarized and $1/f$ noise largely common mode between co-located detectors. Therefore one can overcome these effects by either fast modulation of the polarization sensitivity direction of a single detector (faster than the $1/f$ and scan rate), or by simultaneous differencing of orthogonal pairs of detectors (combined with later re-observation at another angle with the same, or another, pair of detectors) [c].

When modulating the modulator must not change the beam position and shape on the sky. When pair-differencing each half of the pair must have the same beam position and shape on the sky. Inasmuch as these conditions are violated then leakage from the much stronger T and E-mode spectra will occur into the B-mode spectrum.

In general beam imperfections are a fraction of the beam width so they are much more critical for the big beam (small aperture) experiments. However many of the effects at least partially cancel by rotating the telescope with respect to the sky and repeating the observations. Such rotation may take place due to the rotation of the Earth (at non-polar sites) and/or by including an additional line-of-sight (LOS) axis into the telescope mount. For some pair differencing experiments a major problem is "A/B centroid mismatch" where the beams of the orthogonal pair are offset from one another on the sky. This causes leakage from the gradient of T into polarization. However consider rotating by 180 degrees — now the sense of the leakage is reversed and under co-addition it cancels.

Some beam imperfections do not cancel under rotation of the telescope. For this reason some pair-differencing experiments also incorporate a slow (stepped) polarization modulator. So long as the behavior of the upstream optics is polarization independent (a property always required of a modulator) then one can achieve cancellation of beam systematics by repeating the observations at a set of discrete modulation angles.

Analysis mitigation is also possible — if one has knowledge of the beam imperfections and a T map (from another or the same experiment) one can compute the leakage and subtract it

[c] Pair differencing is popular — of all the bolometer experiments mentioned in Table 1 EBEX and PIPER may be the only ones which do not have co-located pairs of detectors.

out. Going further one can instead "project out" the potentially contaminated modes and avoid having to know the beam imperfections a priori. Many frequently referenced estimates of the needed degree of beam performance ignore such observation and analysis based mitigation and hence conclude that much higher beam purity is needed than is in fact the case [15].

3.6 Ground/Balloon/Space

Observing from the ground modern detectors are "background limited" meaning that photon arrival statistics of the atmospheric emission dominate the statistical noise. Thus when observing from above the Earth's atmosphere dramatically better per detector performance can be achieved. However even "long duration" balloon flights are currently $\lesssim 10$ days whereas ground based experiments can and do observe for up to ~ 1000 days. Historically both techniques have delivered final results of comparable quality when equipped with similar numbers of detectors.

Observing from space is a different matter — now one has the low noise level *and* years of exposure. However note that while in principle a CMB spacecraft could concentrate this awesome sensitivity on a small patch of clean sky, in practice — because they have the unique capability to observe the whole sky — they always do. Therefore the deepest small patch maps at any given time are always those from ground/balloon experiments.

4 Current/Future Experimental Efforts

There are a large number of experimental efforts focused on CMB polarization. Table 1 summarizes these with some additional information on each given below.

4.1 Space and Balloon

Planck is a 1.5 m aperture ESA space mission that launched in 2009. The High Frequency Instrument used bolometer detectors similar to those used in the Boomerang, BICEP1 and QUaD experiments, and completed operation in early 2012. The Low Frequency Instrument uses HEMT amplifiers and is still operating. Planck makes full sky maps and improves over WMAP in terms of frequency coverage (9 versus 5 channels), angular resolution ($\sim 3\times$) and sensitivity ($\sim 10\times$). Initial CMB results are expected in early 2013 with polarization results not expected until early 2014.

EBEX is a 1.5 m aperture balloon based experiment funded by NASA which has been under preparation for several years. Its first science flight will be a ~ 10 day circumpolar ("long duration" or LD) flight in Anarctica in late 2012. EBEX has 1500 TES bolometer detectors modulated by a continuously spinning half wave plate at 150, 250 and 410 GHz.

SPIDER is a balloon based array of 0.3 m aperture telescopes funded by NASA. The telescope optics and focal planes are very similar to BICEP2 and Keck-Array. A circumpolar flight is planned for late 2013 with focal planes at 90, 150 and 280 GHz and a total of ~ 2000 TES detectors.

PIPER is a third NASA funded balloon program emphasizing high frequencies (200, 270, 350, 600 GHz) with smaller resolution (~ 0.3 meter) apertures and large numbers of TES detectors (5000 per frequency). Only one frequencies will be active in any given flight and eight "standard duration" (SD) flights are planned split between northern and southern hemispheres. The goal is to cover a large fraction of the sky and target the reionization bump.

4.2 Ground Based in Chile

All the following experiments are (largely) funded by the US NSF and located at various sites in the Atacama desert in Chile.

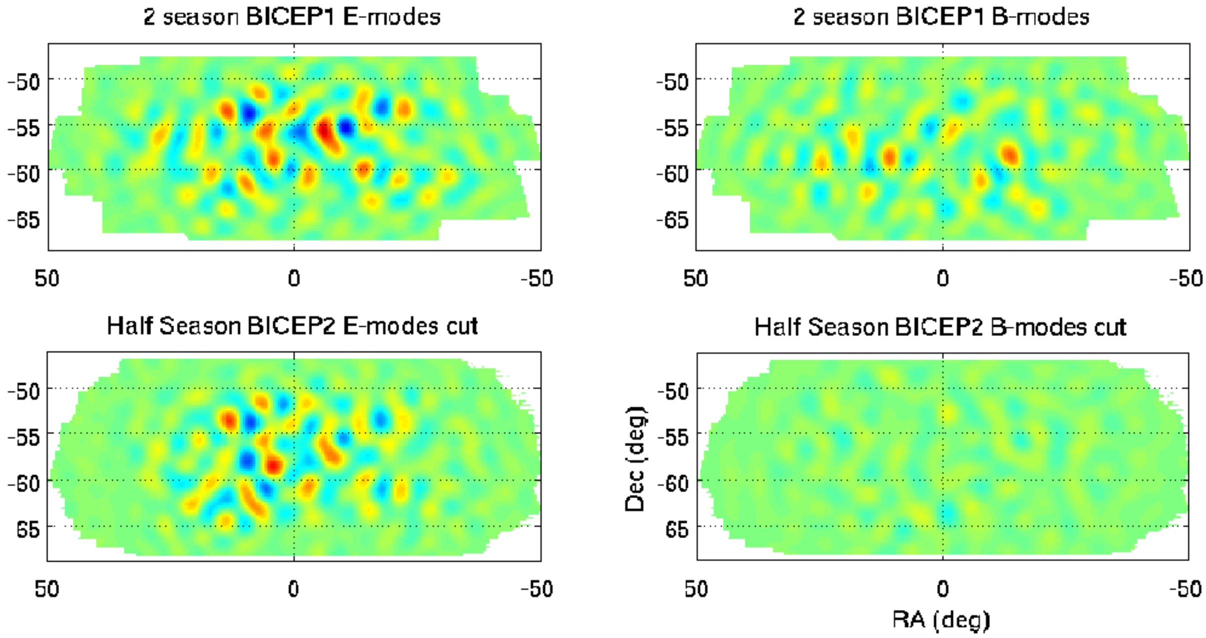

Figure 4: Maps of the CMB polarization E-mode and B-mode filtered to the angular scale range where the inflationary gravity wave signal is expected to be most prominent ($50 < \ell < 120$). The upper maps are the published BICEP1 results which hold the current world record in terms of sensitivity ($r < 0.72$, Chiang et al. (2010)). The lower maps are new preliminary BICEP2 results using half a season of data. The E-mode maps were already signal dominated for BICEP1 and so show little change going to BICEP2. However the BICEP2 B-mode maps show a large decrease in noise due to the much higher sensitivity of the BICEP2 instrument.

QUIET is 1.4 m aperture telescope utilizing HEMT amplifiers. It has released 43 GHz results (see Figure 2), and 90 GHz results are expected soon. It is currently unclear if the QUIET program will continue.

POLARBEAR is a 2.5 m aperture telescope. Deployment was completed in early 2012 and the focal plane is equipped with $\sim$ 1300 TES detectors operating at 150 GHz.

ABS is a 0.3 m all cold reflecting telescope. It has $\sim$ 500 TES detectors at 150 GHz and has been running since early 2012. ABS has a warm waveplate outside the cryostat which spins at 2.5 Hz.

ACTpol is a polarized receiver for the existing 6 m ACT telescope which will deploy in late 2012. ACTpol is *not* emphasizing inflationary B-mode detection.

CLASS is unique amongst ground based experiments in that it is targeting the reionization bump. It will observe at 40, 90 and 150 GHz and deployment is planned to start in 2013.

4.3 Ground Based at South Pole

The following experiments are (largely) funded by the US NSF and located at the South Pole station in Antarctica.

SPTpol is a polarized receiver for the existing 10 m SPT telescope which deployed in early 2012 and is now operating. It has 1500 total TES detectors at 100 and 150 GHz.

BICEP2 is a 0.3 m refracting telescope with 500 TES detectors at 150 GHz. As of mid 2012 it is midway through its third and final season of observation. The proven on sky sensitivity of BICEP2 is $\sim 10\times$ higher than that of BICEP1 — comparable to that of the Planck spacecraft but concentrated on a small patch of ultra clean sky. Figure 4 shows E and B-mode maps from BICEP2.

Keck-Array (aka SPUD) is an array of BICEP2 like telescopes. It operated through the 2011 season with three receivers at 150 GHz, and is operating for 2012 with five such receivers. For future seasons some receivers may be reconfigured to 90 and/or 220 GHz.

Table 1: Parameters of current and upcoming CMB telescopes.

Name	Type	Deploy/Fly	Aperture	Freq. (GHz)	Detectors	Modulation[a]
Planck	Space	2009	1.5 m	30–860		PD/LOS
EBEX	LD Balloon	late 2012	1.5 m	150/250/410	1500 TES	SR/FM
SPIDER	LD Balloon	late 2013	0.3 m	90/150/280	2000 TES	SR/PD/SM
PIPER	SD Balloon	9/2013	$\sim$ 0.3 m	200/270/350/600	5000 TES	SR/FM
QUIET-I	Chile	2008–10	1.4 m	40/90	19/90 HEMT	SR/FM/LOS
POLARBEAR	Chile	early 2012	2.5 m	150	1300 TES	SR/PD/SM
ABS	Chile	early 2012	0.3 m	150	500 TES	SR/PD/FM
ACTpol	Chile	late 2012	6 m	90/150	3000 TES	SR/PD
CLASS	Chile	late 2013	?	40/90/150	?	SR/?
SPTpol	South Pole	early 2012	10 m	100/150	1500 TES	PD
BICEP2	South Pole	early 2010	0.3 m	150	500 TES	PD/LOS
Keck-Array	South Pole	early 2011	0.3 m	150	2500 TES	PD/LOS

[a] SR = sky-rotation, FM/SM = fast/slow modulator (HWP, VPM or phase-switch), PD = pair-difference, LOS = line-of-sight rotation of whole telescope.

4.4 Future Space Mission?

The 2007 Bpol proposal to ESA consisted of an array of small refracting telescopes and was not selected. The US 2010 Decadal Survey recommended that NASA reconsider a future CMB space mission mid-decade. In 2010 the European community tried again with the more ambitious 1.2 m 6000 detector COrE mission which incorporated a large reflective polarization modulator. This was rated just below the selection cutoff for further study.

5 Conclusion

Inflation is often talked about as a part of the "standard cosmological model". It is perhaps more correct to say that this audacious theory is compatible with observations — it naturally produces the sort of Universe in which we find ourselves: spatially flat, isotropic and with scale-free, adiabatic initial conditions. It is therefore of critical importance to search for the final, and so far unobserved, prediction of Inflation — a background of primordial gravitational waves. If such waves exist at the time when the CMB photons last scatter they will imprint a very specific B-mode polarization pattern.

This paper has described the optimizations and trade-offs necessary to search for the gravitational wave signal in terms of frequency, sky-coverage, detector technology, modulation and experiment location. The current experimental "landscape" has also been summarized: many groups are pushing hard to detect this possible signal using a range of approaches, and emphasizing different parts of the problem. If nature is kind, and $r \geq 0.02$ then we should detect it soon!

Acknowledgments

The author wishes to thank his collaborators and many other members of the CMB community for useful discussions, the NSF (grant number ANT-1110087) for funding, and the conference organizers.

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